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EFG SOLAR MODULES

Program Manager: Ronald S. Scharlack

Final Report - Subcontract No. 954999

Covering Period: March 31, 1978 - August 31, 1978

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"The JPL Low-Cost Silicon Solar Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DoE."

ABSTRACT

Six photovoltaic modules using solar cells fabricated from silicon ribbons were assembled and delivered to JPL. Each module was comprised of four separate submodules which were parallel connected. The submodules contained 45 EFG cells which were series interconnected by a "shingle" or overlapping design. The inherent rectangular shape of the cells allowed a high packing factor to be achieved. The average efficiency of the six modules, corrected to AM1 at 28°C was 8.7%, which indicates that the average encapsulated cell efficiency was 10.0%.

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1.0 INTRODUCTION

The purpose of this program was to design and deliver to JPL the first photovoltaic modules made with a second generation silicon sheet technology. A goal of the program was that the six modules, fabricated with Mobil Tyco's EFG silicon cells, should have an efficiency exceeding 8%. The module design is representative of a technology that can lead to an array cost of $0.50 per watt.

The modules were subjected to preliminary testing at Mobil Tyco and a local test facility before shipment to JPL. The results of these tests indicated that the average module efficiency was 8.7% and that the design was capable of surviving the JPL acceptance tests. During the packing of the first three modules, it was noted that some of the submodules had developed cracks at the terminal holes in the substrate. Mobil Tyco has redesigned the terminal attachment and has developed a new method which eliminates the hole in the rear substrate by making the electrical connection pass through the submodule seal. Two modules with the redesigned terminals and one module with the through-the-seal connection were shipped to JPL. The last three modules show no signs of the cracking associated with the first three modules.

2.0 EFG SILICON RIBBON SOLAR CELLS

The edge defined film-fed growth (EFG) technology for the production of shaped crystals of silicon is the first of the second generation sheet technologies to have reached a stage of maturity to permit the fabrication of significant quantities of high efficiency photovoltaic modules. The EFG process employs shaping capillary dies made of graphite to grow ribbon shaped crystals of silicon. These crystals are nominally 2.5 cm in width x 0.025 cm in thickness and are grown in continuous lengths up to 30 meters. Current generation ribbon solar cells are nominally 2.5 cm x 10 cm in dimensions and energy conversion efficiencies in excess of 10% (AM1) are routinely achieved using fairly standard solar cell processing techniques.

The principal advantages of the EFG technique include the ability to grow crystals of predetermined shape, the achievement of high growth rates and the ability to grow multiple ribbon from a single growth machine.* SAMICS analysis of the multiple ribbon growth technology has indicated that silicon sheet costs below $18/sq meter consistent with the $0.50/watt goal of the national photovoltaic program can be achieved.

Ribbon solar cells employed in the production of modules under this contract have been fabricated by conventional diffusion and metallization techniques. The basic process consists of the following sequence:

1. Acid clean as cut ribbon blanks (1" x 4" dimensions) using a low concentration mixture of HF and HNO_3.
2. N^+ diffusion using 1% PH_3 in a carrier gas composed of N_2, O_2 and Ar to achieve a surface concentration of 10^{20} atoms/sq. cm and a junction depth of 0.4 μm.
3. Remove diffusion oxide in buffered HF and evaporate aluminum on the "back side" of the device.

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* On an experimental basis ribbons of width up to 7.5 cm have been grown and growth rates up to 7.5 cm/min. have been achieved. In addition five 5 cm wide ribbons have been grown simultaneously from a single multiple ribbon machine.

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4. Alloy aluminum to counterdope back N^+.
5. Buffered HF clean.
6. Contact evaporation using Cr-Ti-Ag with a total metal thickness of 1.5 μm.
7. Sinter contact metal.
8. Mask etch cell edges.
9. Solder coat.
10. Deposit Si_3N_4 antireflection coating.

3.0 MODULE DESIGN

The Mobil Tyco photovoltaic module has been designed to survive extreme environmental conditions for 20 years yet incorporate features which can lead to a low cost packaging system for silicon solar cells. Full consideration has been given to problems of differential thermal expansion, mechanical stress and package degradation.

3.1 General Module Description

The Mobil Tyco module consists of four separate submodules, each of which contains 45 EFG cells, which are series interconnected, to provide the nominal output voltage. The four submodules are parallel interconnected to give higher current at the operating voltage. Figure 1 shows an overall layout of the module and submodules. Three strings of 15 cells are first formed; these strings are then interconnected, as shown in Fig. 2, to form the 45 cell submodule. Figure 3 shows a cross section of the module construction. The photographs in Figs. 4 and 5 are of modules similar to those shipped to JPL.

3.2 Cell Interconnection

The EFG ribbon cells are interconnected with Exmet 3Cu6-3/0, expanded copper mesh. The mesh extends across the length of the cell thereby providing redundant electrical connection along the cell bus bar. The expanded mesh provides flexibility for the differential thermal expansion between both the silicon and copper, and between the silicon and glass cover and substrate. The copper mesh is solder plated to allow reflow soldering to solder coated solar cells, thereby eliminating a flux cleaning step. The interconnect scheme utilizes a shingle style or overlapping design which covers the bus bar and thus provides a higher packing factor.

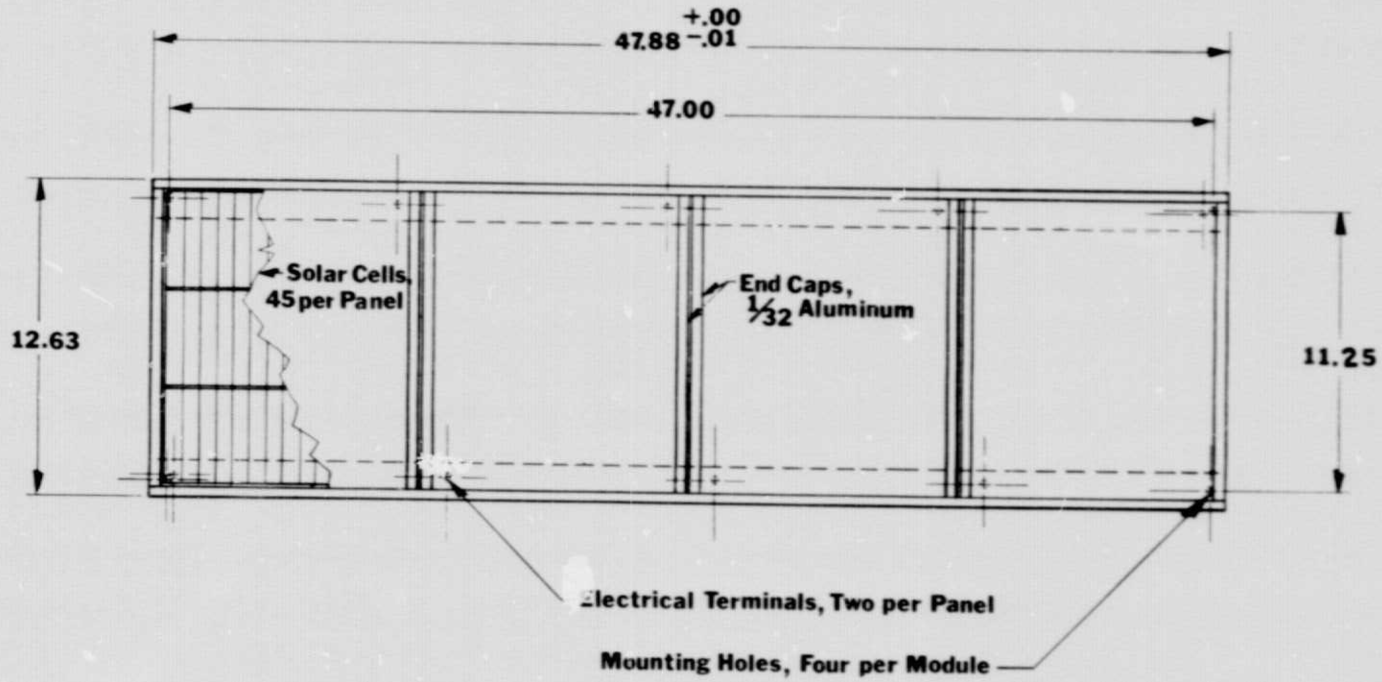

Fig. 1. Layout of Module and Submodule.

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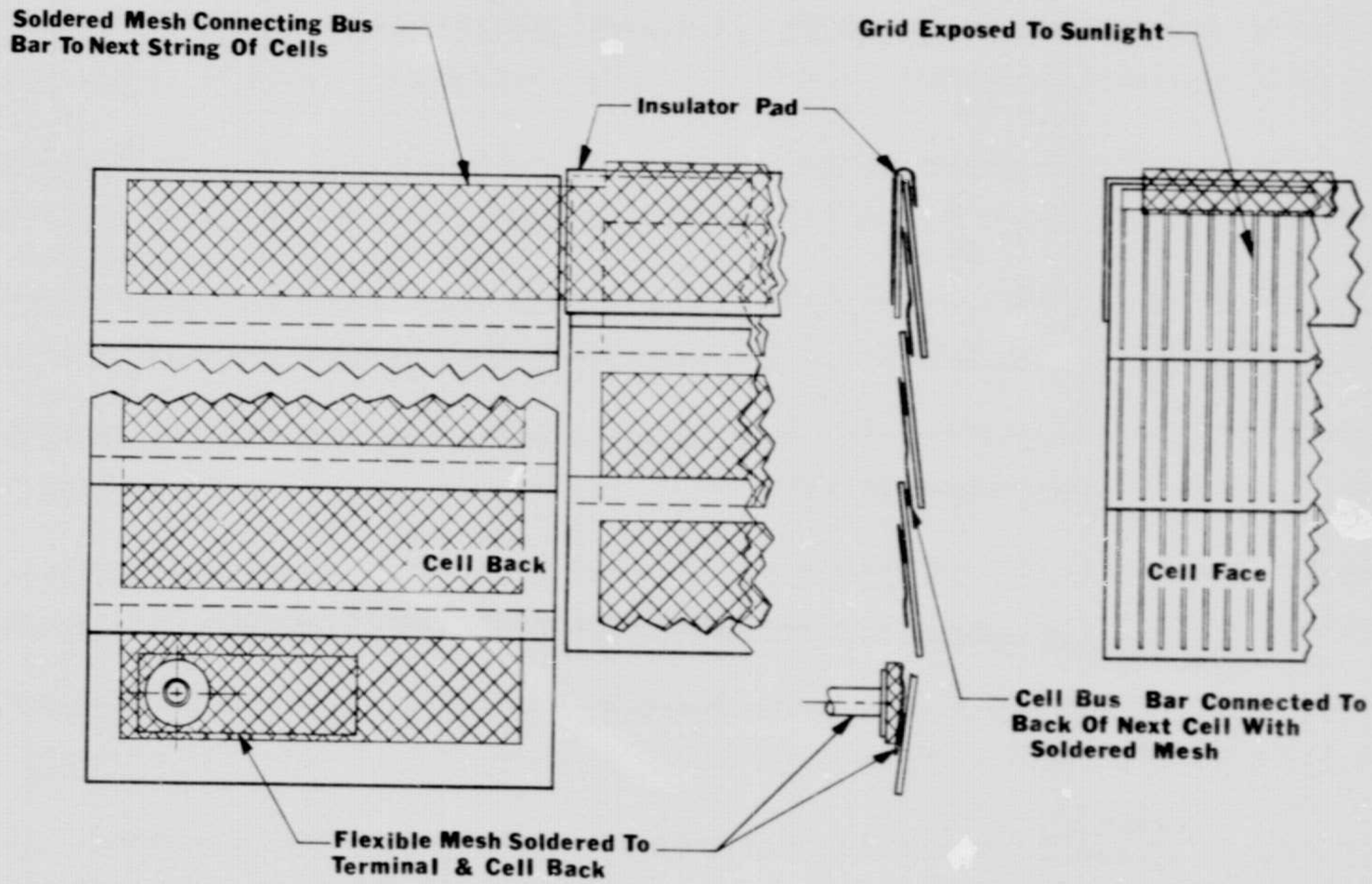

Fig. 2. 45 Cell Submodule

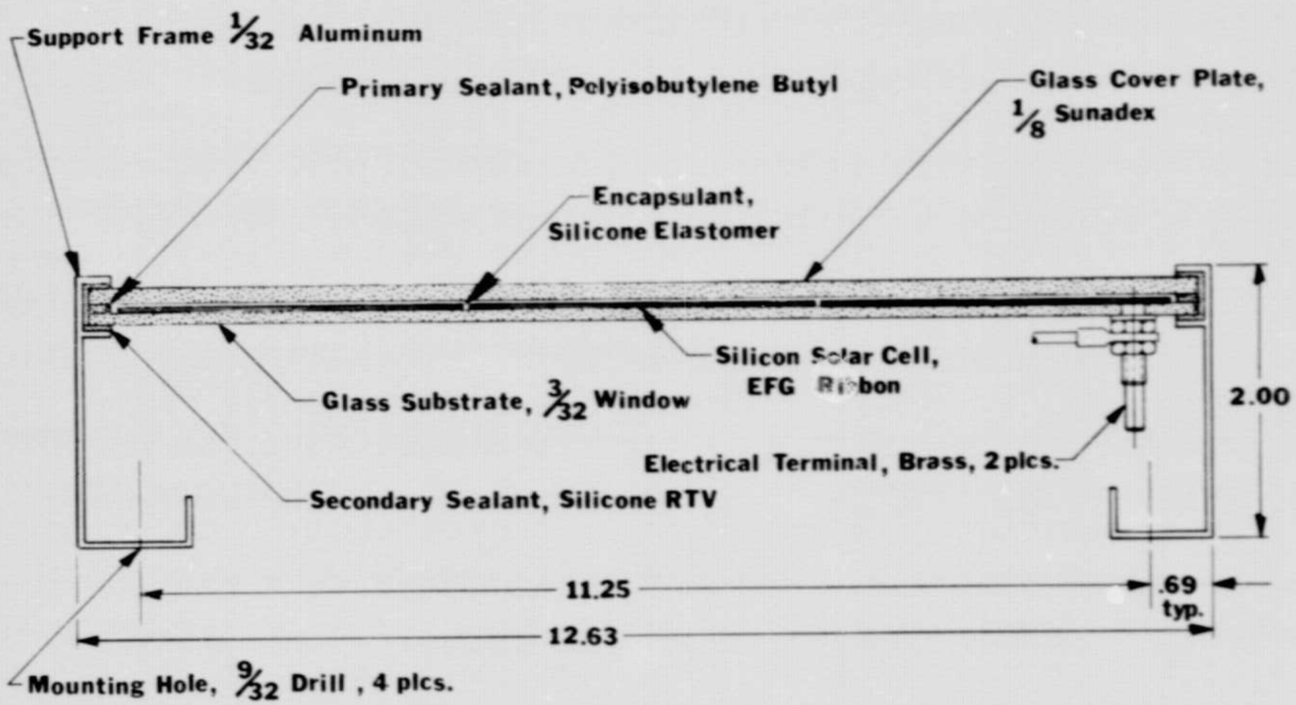

Fig. 3. Cross-section of Module

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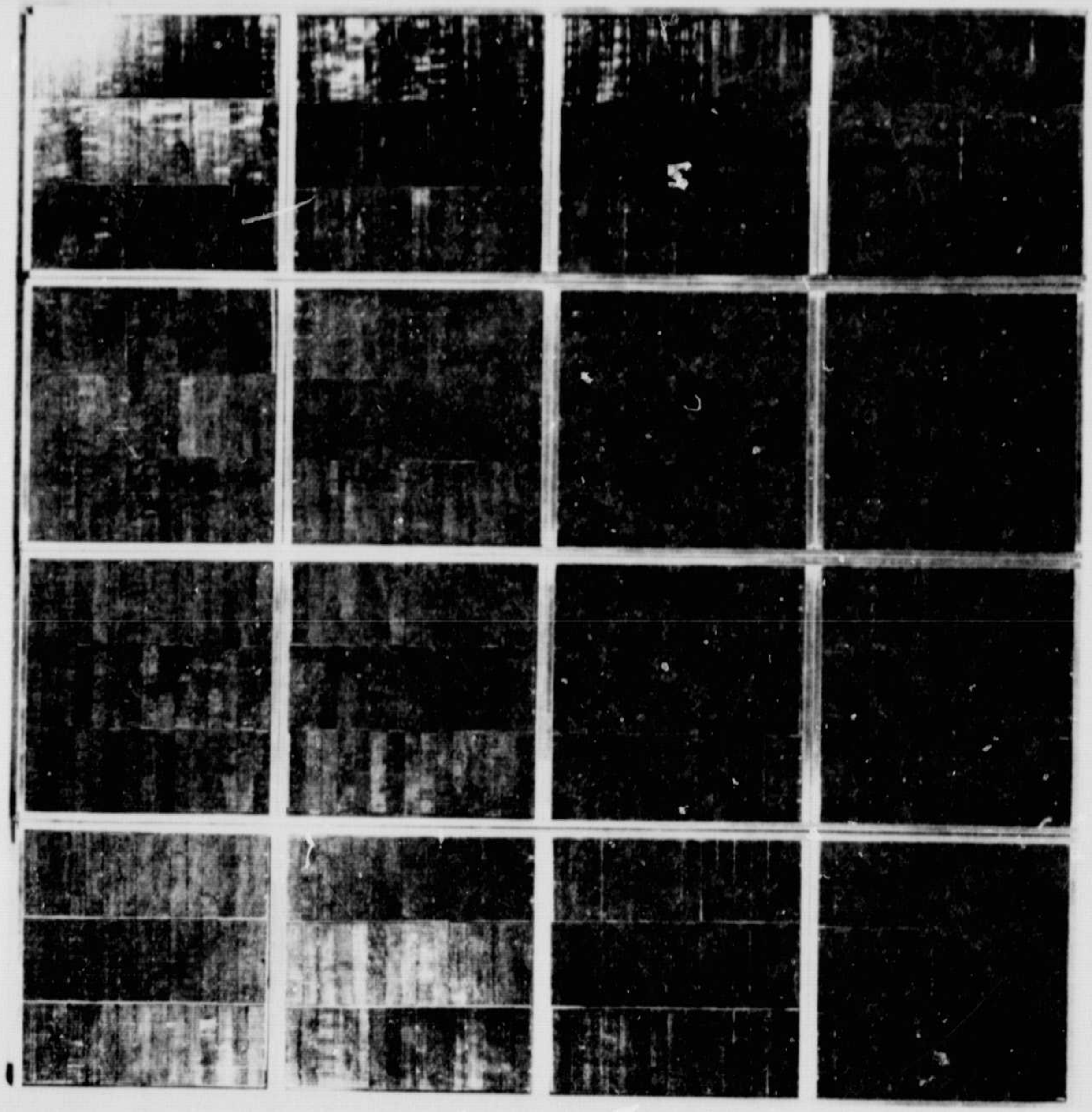

Fig. 4. EFG Array (Submodules are 1 ft x 1 ft. Array is 4 ft x 4 ft)

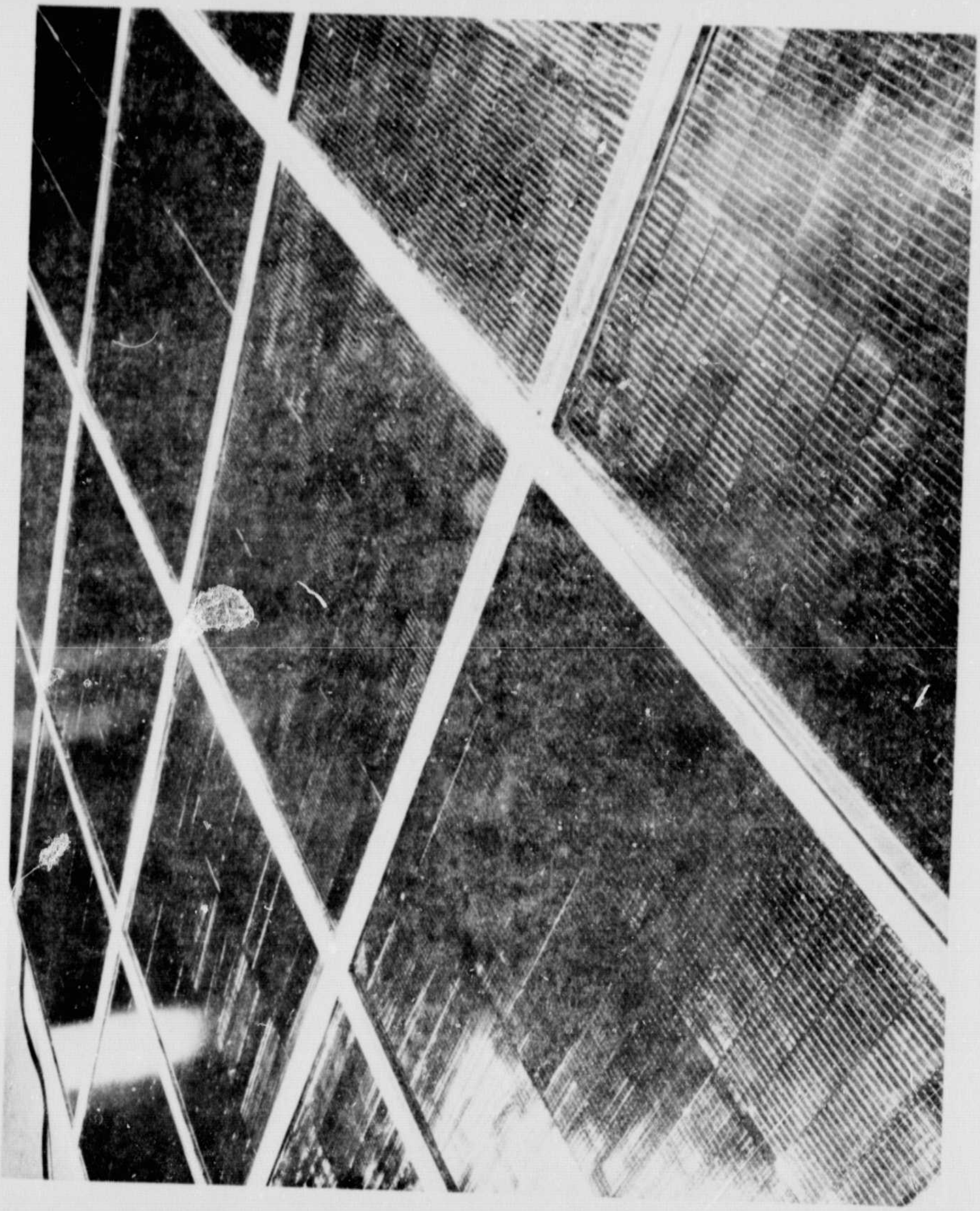

Fig. 5. EFG Array

3.3 Module Encapsulant

The cells are encapsulated with Dow Corning Sylgard 184 which provides good mechanical isolation for the cells. The low elastic modulus of the Sylgard allows differential expansion between the cells and the glass covers. Shock and vibration are also minimized. Sylgard provides electrical isolation between cells and module components, while its high transmissivity and refractive index provide a good optical coupling between the front cover and the solar cells. The bonding surfaces are first primed to ensure good adhesion with the encapsulant.

3.4 Module Cover and Substrate

Glass was chosen as the cover and substrate material because it provides a hermetic barrier to environmental degradation agents, has an inherently low coefficient of thermal expansion, provides excellent electrical isolation and provides a low cost package. ASG Sunadex glass 1/8 in. thick was selected for the front cover because of its low iron oxide content and therefore high transmissivity over the wavelengths of interest. The substrate is 3/32 in. ASG floatglass.

3.5 Edge Seals

The edge seal between the glass sheets is provided by a two component system. The primary seal against moisture is achieved with Tremco 750-55X polyisobutylene butyl. It is widely used in glazing insulating glass, can be applied with a variety of techniques which are commercially available, and is low in cost. The secondary seal is formed with GE IGS 3100 silicone sealant; it provides an excellent water barrier in addition to bonding the glass to the aluminum rails. This silicone sealant is also low in cost and readily applied, but a switch to a 2 part silicone sealant is anticipated in the near future.

3.6 Electrical Terminals

The module electrical terminals are solder plated brass and are designed to provide an encapsulant filling means without additional panel intrusion. An alternative electrical termination method and encapsulant filling scheme are described in Section 5, Rear Terminal Redesign.

3.7 Module Structural Components

The structural strength for the four foot long module is provided by anodized aluminum extrusions along the sides of the module. End caps are used to give edge support and protection.

4.0 MODULE FABRICATION

4.1 Interconnection of Cells

EFG solar cells are graded by current and voltage to improve module performance by matching cells of similar characteristics. After testing, the cells have the expanded copper mesh soldered to the bus bars; then the cells are overlapped and the mesh is soldered to the cell backs. Strings of 15 cells, formed in this way, are then checked for performance and matched with other strings for assembly into submodules. After the strings are series interconnected, the assembly is again checked for performance.

4.2 Cell Encapsulation

The cells are now placed on the substrate, leads are soldered to the output terminals and the cover glass, to which the primary sealant has been applied, is set in place and the sealant compressed. Encapsulant is then introduced into the glass sandwich through the terminal studs. The filled submodule is allowed to cure and is then cleaned and its performance recorded for matching with other submodules.

4.3 Module Assembly

End caps of extruded aluminum are partially filled with silicone adhesive and positioned on two of the submodule sides. After the silicone has hardened, the submodules are positioned into the side rails, in which additional silicone adhesive has been placed. After hardening of the adhesive the submodules are cleaned, electrical leads are attached, and the final testing of the completed module is made.

5.0 REAR TERMINAL REDESIGN

Some cracks in the glass substrates of the submodules were noted in the first three modules delivered to JPL. The delivery of the remaining modules was postponed to allow time to redesign and test a new electrical termination since the cracks appeared at the terminal holes. Two satisfactory solutions to the terminal hole cracking problem were achieved. The first was a revision of the terminal attachment procedure to ensure that both proper clearance between the stud and the hole is obtained, and that the mounting is resilient.

5.1 Terminal Mounting Design

Testing of drilled glass samples revealed that the probable source of the cracking problem was from the method of attachment rather than from the drilled hole itself. Therefore, a redesigned mounting procedure was selected which assured good mechanical isolation between the terminal and the glass. A relatively thick bond of flexible epoxy attaches the terminal flange to the inside of the substrate, and a low durometer silicone rubber washer is inserted between the glass and the terminal washer and nut (see Fig. 6).

5.2 Through-the-Seal Terminal Design

A design to eliminate the drilled hole and terminal for the glass substrate was developed. The electrical termination is made by passing an insulated flat copper braid through the edge seal and attaching it, with the interconnecting wires from other submodules, to the frame by means of a nylon strain relief (see Fig. 7). An interim process has been developed for satisfactorily porting the encapsulant to the glass panel.

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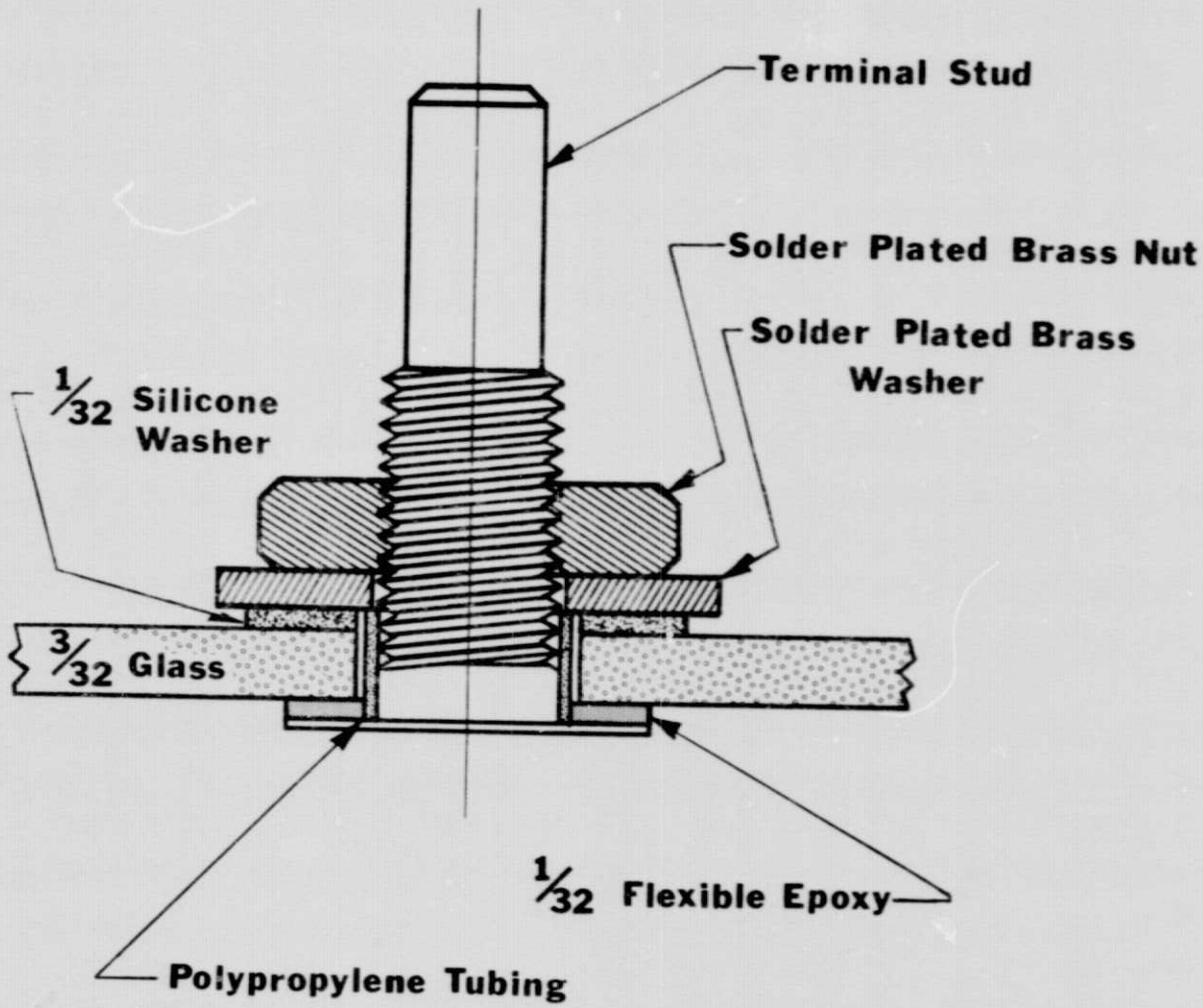

Fig. 6. Terminal Attachment

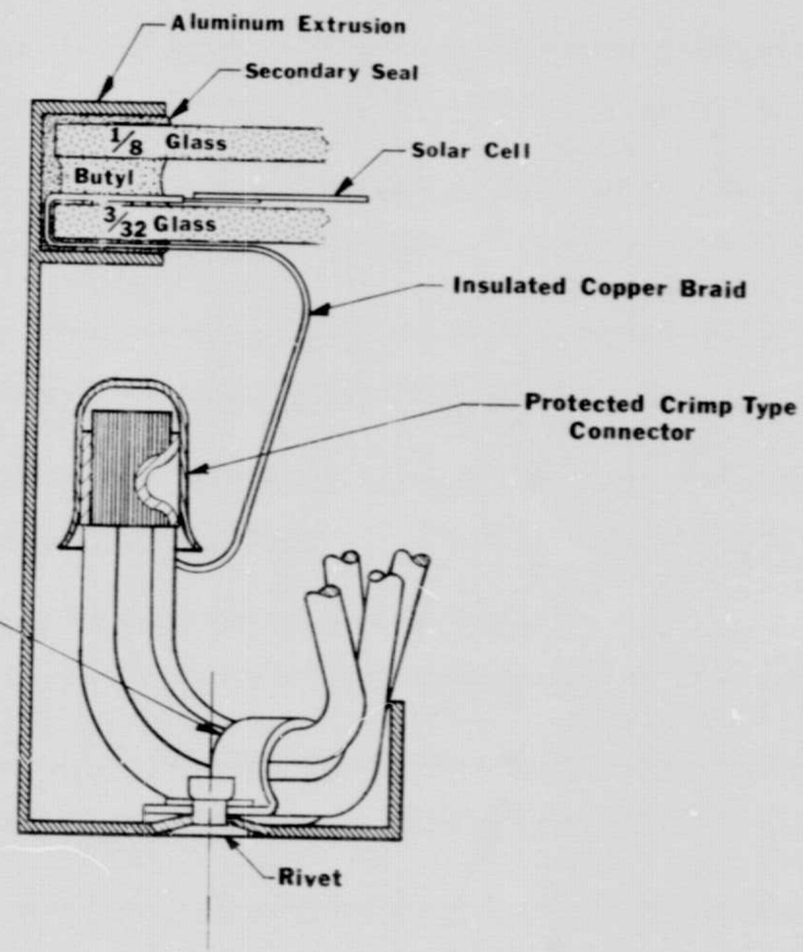

Fig. 7. "Through-the-Seal" Electrical Termination.

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6.0 TEST PROGRAM

6.1 Introduction

The testing program was carried out to ensure that the solar modules would meet the necessary requirements of electrical performance and environmental durability. Most of the testing was carried out at Mobil Tyco; the only exception was the thermal cycling of completed modules, carried out in Wilmington, Massachusetts by Avco Environmental Testing Service. This was necessary because the in-house environmental chamber was too small to accommodate the full-sized modules.

Electrical testing consisted of performance and electrical isolation tests. Because the long-arc Xenon simulator was not yet operational, all final performance testing was made in natural sunlight. A conventional four-wire system connected the modules to a load box, where the illuminated I-V curves were drawn using an X-Y recorder. Submodule testing was automated in mid-July with a DEC PDP-11/03 microcomputer. Electrical isolation tests were made using a high voltage, programming power supply (KEPCO, Model ABC 1500 M).

Environmental testing consisted of humidity and temperature cycling. A temperature chamber (Conrad/Missner, Model FB1.5-120) was used to cycle submodules. Mechanical stress tests were implemented with weighted sandbags.

6.2 Cell Testing

Individual solar cells are tested on a temperature-controlled fixt[illegible] under two ELH simulator lamps. The fixture is interfaced with a DEC PDP 11/03 microcomputer which checks the contact resistance, takes the measurements, stores the data, and matches the cells for panel production on the basis of current at peak power. Shorted and poor-performance cells are rejected at this stage.

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6.3 Submodule Testing

Each completed submodule first undergoes four cycles (24 hours) in the temperature cycling chamber, in order to eliminate failures due to infant mortality. This has generally had no apparent effect on the performance or the appearance of the submodules, but in a few instances there has been some formation of air bubbles in the encapsulant.

The electrical performance tests have been carried out in natural sunlight, using a calibrated reference cell to measure light intensity. Temperature control is achieved by allowing the covered submodules to come to thermal equilibrium with the air. The I-V curves are measured immediately after the submodules are uncovered.

Using the air temperature, T , and the light intensity, E , the I-V data is adjusted to standard conditions (100 mW/cm^2 and 28°C) with the following voltage, V , and current, I , transformations:

$$I' = I + I_{sc}\,(100/E - 1) + \alpha(28 - T)E$$

$$V' = V + \beta(28 - T)\,N - R_s(I' - I)$$

where

α	=	current temperature coefficient
β	=	voltage temperature coefficient
R_s	=	submodule series resistance
N	=	number of series-connected cells in the submodule (generally 45).

There is one small additional term, known as a curve correction term, which is often used in the voltage transformation to soften the knee of the I-V curve with increased temperature. Data has been too scarce at this point to calculate the value of this term, so it has not been used.

Initial values for α, β, and R_s were calculated using data from several submodules mounted on the roof which have been measured under a variety of conditions. These submodules, however, were constructed about a year ago and their design differs substantially from that of current submodules, so the initial values probably no longer apply. JPL calculated values for α and β using the three modules received in May; these values are in better agreement with the available literature and have been used subsequently. Both are listed below:

	(mA/°C/100 mW/cm^2)	(mV/°C/ccU)
original value	1.48	2.0
JPL value	0.544	2.2

Submodule series resistance is calculated for each submodule from the slope of the I-V curve at open circuit voltage. Values range from 1.5 to 3.5Ω. or about .03 to .07Ω/cell. Prior to the test automation, a value of 3.5Ω was used for all submodules, a value which has since proven to be too large.

The data printouts contain both raw and transformed data, as shown in Table 1. Figure 8 shows an example of the transformed curves which are used to match the submodules for assembly into modules. Module test data can be found in Tables 2 and 3. Table 2 compares MTSEC and JPL data for the first three modules and Table 3 provides data on the second three modules.

6.4 Module Testing at Mobil Tyco

6.4.1 Electrical

Electrical performance tests were done in natural sunlight, and transformations to standard conditions were made in the same way as for submodules. I-V curves were drawn with an X-Y recorder, however, since module current output is out of the range of the automatic data acquisition system.

Electrical isolation and voltage withstanding tests were carried out on each completed module. After shorting the output terminals together, +1000 and then -1000 volts was applied between the terminal and the frame for at least one minute for each polarity, checking that the current did not exceed 10 μA. Then 1500 volts was applied and also held for at least one minute, checking that the current did not exceed 50 μA. In general, the modules performed very well in these tests, showing less than 2 μA at 1500 volts.

6.4.2 Environmental

Humidity cycling tests were made on eight submodules before the beginning of the contract and showed no significant change in performance. These tests have not been repeated on any recent modules.

6.4.3 Mechanical

The mechanical integrity test was performed using a sandbag loading technique. Two hundred-forty pounds of sand in plastic bags was distributed over the raised module, representing an approximate load of 56.6 lbf/ft^2. The load was alternately placed on the front and back glass several times. Two modules were subjected to this test; neither was damaged.

Table 1. Submodule Data Summary

RAW PANEL DATA

DATE: 9/6/78

Panel No.	V_{oc} (V)	I_{sc} (A)	PP (W)	Incident Power (mW/cm^2)	Temp. (C)
345	24.9	0.351	6.4	73	28
346	24.6	0.323	5.2	67	28
347	23.3	0.335	5.4	71	28
348	24.9	0.340	6.0	71	28
349	22.7	0.319	5.1	70	29
350	23.8	0.307	5.2	69	28
Mean Values:	24.0	0.329	5.6	70	

Total Power Generated Is 33.3 watts

Comments:

DATA TRANSFORMED TO STANDARD CONDITIONS

DATE: 9/6/78

Panel No.	V_{oc} (V)	I_{sc}(A)	PP (W)	FF	EFF (%)
345	25.2	0.481	9.0	0.743	9.50
346	25.1	0.481	8.4	0.696	8.85
347	23.7	0.472	7.9	0.706	8.33
348	25.3	0.478	8.7	0.725	9.23
349	23.2	0.456	7.5	0.713	7.94
350	24.3	0.445	7.8	0.719	8.19
Mean Values:	24.5	0.469	8.2	0.717	8.67

Total Power Generated Is 49.3 watts

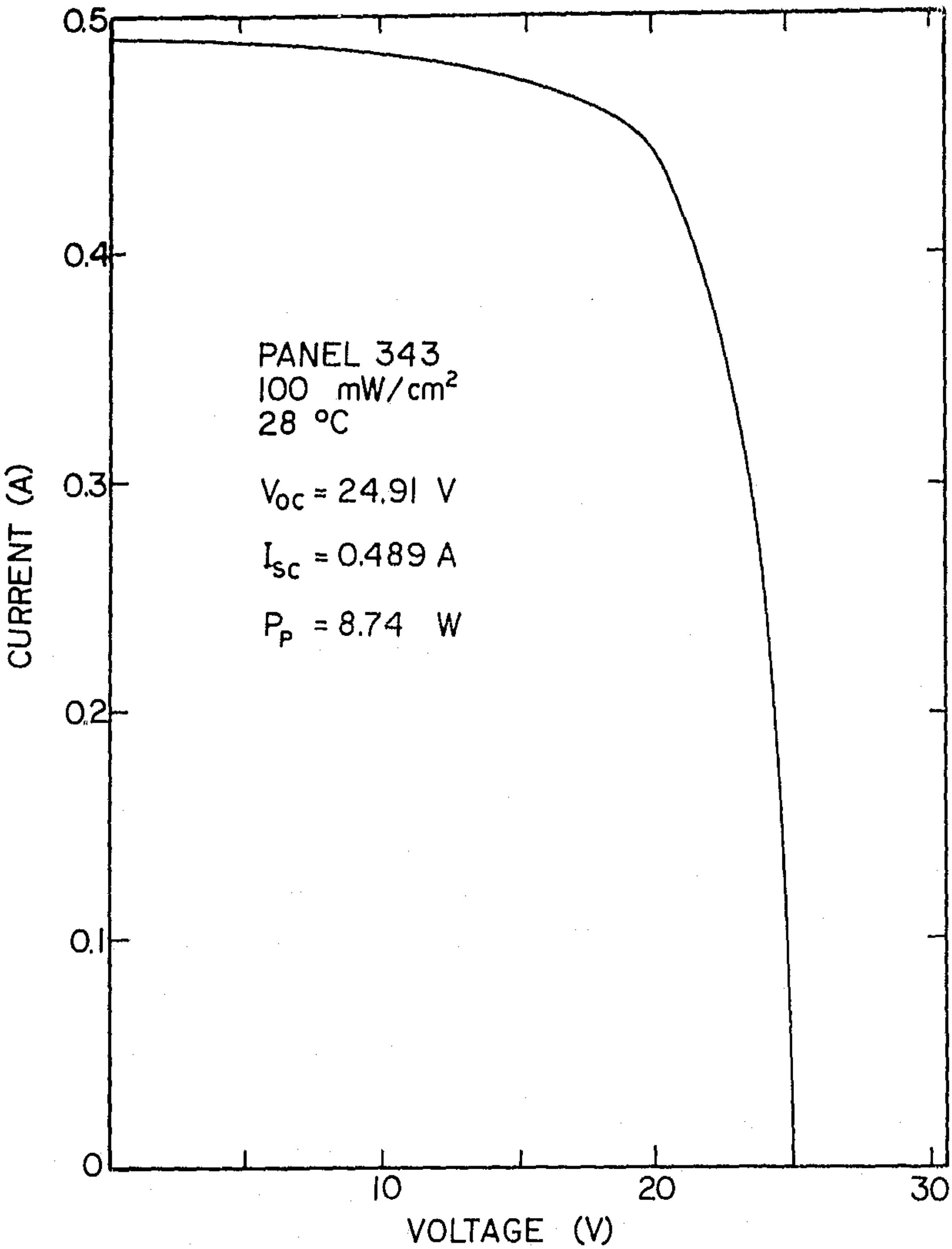

Fig. 8. Submodule I-V Curve

Table 2. Comparison of JPL and Mobil Tyco Solar Energy Corporation (MTSEC) Measurements Made on Three Solar Modules Delivered to JPL. All data transformed to 100 mW/cm^2 and 28°C.

Module No.	V_{oc} (V) MTSEC	V_{oc} (V) JPL*	I_{sc} (A) MTSEC	I_{sc} (A) JPL*	P_{max} (W) MTSEC	P_{max} (W) JPL*
1	24.6	25.1	2.03	1.96	35.9	35.7
2	24.2	24.7	1.95	1.88	33.3	32.8
3	24.1	24.6	2.00	1.95	33.0	32.7

Detailed examination of the data shows that exact agreement would be obtained if the MTSEC temperature measurement was 5° too low and the intensity measurement was 2 mW/cm^2 too high.*

Table 3. Data for the Final Three Modules (MTSEC Data).

Module No.	V_{oc} (V)	I_{sc} (A)	PP (W)	FF
4	24.7	1.951	34.1	.707
5	24.2	1.934	32.3	.689
6	24.6	1.778	31.5	.720

* Since those tests were made JPL has determined that the simulator used at JPL may have been inaccurate to the extent of being ~6% lower in intensity than assumed.

6.5 Module Testing at JPL

To date three of the six delivered modules have completed JPL environmental tests. All tests have been successfully completed with no module electrical degradation. The JPL test summary sheet is attached as Table 4.

Table 4. (JPL Data)

Vendor Mobil-Tyco Block Task 4 Rating Voltage NCOI

ID Number	Line	Test/ Duration	JPL PM, W	Delta PM, Pct	Flash Date	I	P	Delta P, Pct	ISC	VOC	IMP	VMP	FF	P/F
KL-001-AT	1	RCVG	32.11		06/21/78	J	28.27		1.772	25.01	1.538	20.88	.72	Encapsulant
KL-001-AT	2	S/A-15-1	32.08		07/20/78						Split Glass Substrate Cracked			
KL-001-AT	3	T-50	32.07	0.0	07/31/78		Satisfactory							
KL-001-AT	4	H-5	32.36	+0.9	08/10/78		Satisfactory							
KL-001-AT	5	M-100	32.09	0.0	10/11/78		Satisfactory							
KL-002-AT	1	RCVG	29.59		06/21/78		26.05		1.712	24.66	1.455	20.34	.70	Glass Sub-
KL-002-AT	2	S/A-15-1	29.33		07/20/78						strate Cracked at + Terminal			
KL-002-AT	3	T-50	29.35	+0.1	07/31/78		Delaminated 12 Cells							1428
KL-002-AT	4	H-5	29.30	-0.1	08/10/78		Satisfactory							
KL-002-AT	5	M-10G	29.37	+0.1	10/11/78		6mm Edge Crack 1 Cell							1440
KL-003-Cϕ	1	RCVG	29.39		06/21/78		25.57		1.757	24.41	1.496	19.65	.69	Cell Cracked
KL-003-Cϕ	2	No Test	29.31	-0.3	07/20/78		Control Module				Glass Cracked			1418
KL-003-Cϕ	3	No Test	29.50	+0.4	07/31/78		Control Module							
KL-003-Cϕ	4	No Test	29.55	+0.5	08/10/78		Control Module							
KL-003-Cϕ	5	No Test	29.52	+0.4	10/11/78		Control Module							
KS/A-15-1	1	Initial	61.71		07/20/78				3.497	24.81	3.010	20.50		S/A-15-1
KS/A-15-1	2	T-50	60.60	-1.8	07/31/78									15-L-001,L-002
KS/A-15-1	3	H-5	60.75	-1.6	08/10/78									
KS/A-15-1	4	M-100	60.75	-1.6	10/11/78									

1. As-received
2. Immediately before testing
3. After 50 cycle temperature test
4. After 5 cycle humidity test
5. After 100 cycle stress test

7.0 CONCLUSIONS

The design, development and fabrication of six EFG silicon photovoltaic modules was achieved. The modules had high packing density and good efficiency due to the inherent rectangular shape of EFG ribbon cells. The module design incorporated features that are applicable to low cost designs which can lead to the achievement of the $0.50 per peak watt goal.

Problems with the cracking of the substrate were eliminated by redesign of the electrical terminations. Two solutions were developed, both of which will be considered for future designs. Module efficiencies exceeding 9% have been achieved using current generation EFG silicon ribbon solar cells.